7th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 14–18, 1999

Electric field induced interference impurity ionization in coupled quantum wells

Yu. A. Aleshchenko, I. P. Kazakov, V. V. Kapaev, Yu. V. Kopaev,
N. V. Kornyakov and A. E. Tyurin
P. N. Lebedev Physical Institute of RAS, 117924 Moscow, Russia

Abstract. The dramatic change of Si donor impurity ionization energy was experimentally found in GaAs/AlGaAs double-well structure. This effect accompanies the rearrangement of electronic wave function in electric field. With less than 1 V variation of the bias on the structure the impurity ionization energy falls to zero from 15.5 meV. The Stark effect should cause the variation of this parameter no more than 3 meV.

Introduction

The quantum interference of electronic states in coupled quantum wells (QWs) causes a high sensitivity of the system to the external exposures. In these circumstances even relatively weak electric field gives rise to the drastic modification of electronic wave functions (WFs) and their redislocation between QWs. We have predicted earlier [ ] the effect of impurity ionization energy (E_{imp}) modification caused by such redislocation. The inversion of lower subbands of coupled QWs with their anticrossing in external field is responsible for this effect. The localized state of the electron on impurity atom which is formed mainly from the states of the lower subband changes its binding energy and the shape of WF as a result of inversion. Here we verify this effect by photoluminescence (PL) spectroscopy in GaAs/AlGaAs double-QW structure in external electric field.

1 Experimental procedure

The structure under study was grown by MBE on GaAs(100) substrate. The active layers of the structure comprised lower undoped 57 Å QW, 34 Å $Al_{0.34}Ga_{0.66}As$ barrier and 79 Å upper QW with Si δ-doping ($n = 6.3 \times 10^{11}$ cm^{-2}) in its centre. The PL was excited by 4880 Å line of Ar^+ laser at 20–90 K.

2 Experimental results

The PL peaks assignment was made by comparison of experimental spectra taken at zero bias ($U = 0$) with the results of simultaneous solution of Shrödinger and Poisson equations. The potential profile in the region of QW of the structure to be investigated as well as calculated WFs for three lower electron and heavy hole subbands at $U = 0$ are sketched in Fig. 1(a). One can see from the figure that the distortion of potential profile by built-in field causes the localization of ground state electron and hole WFs (curves 1) in different QWs. As a result the overlap integral for the transition between first electron and heavy-hole subbands (c1–h1) appears to be considerably lower than for transitions connecting second electron and first heavy-hole (c2–h1) as well as first electron and second heavy-hole (c1–h2) subbands which WFs are localized in the same QW.

The PL spectrum of the structure taken at 20 K and $U = 0$ with the excitation intensity of 4 W/cm^2 is shown in Fig. 1(b) by solid line. The narrow peak at 1.599 eV dominates

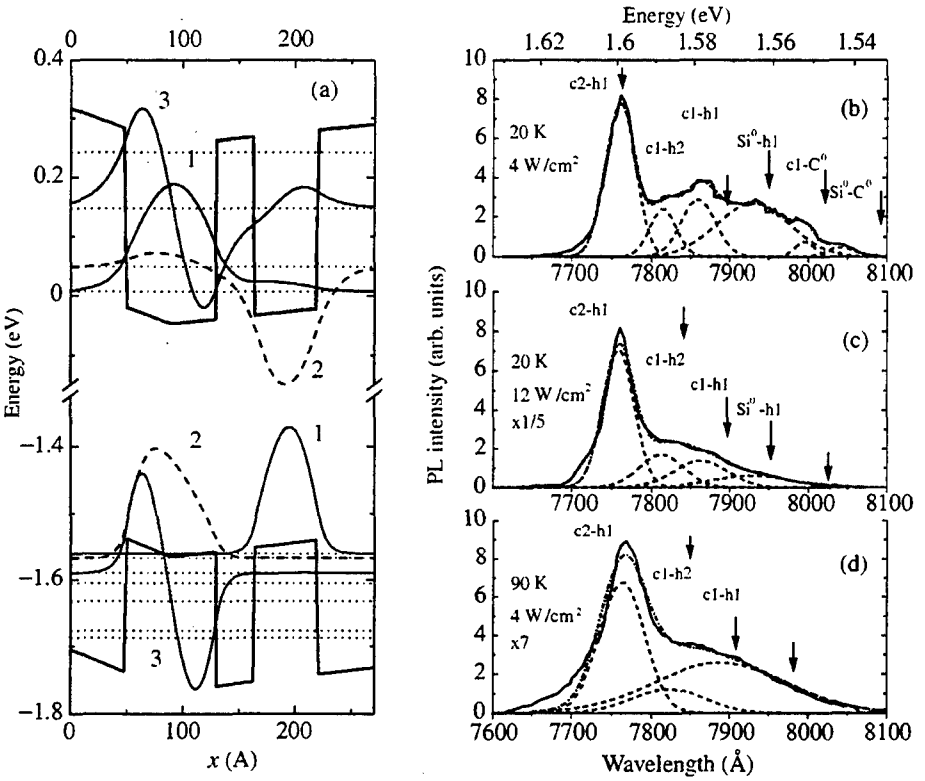

Fig. 1. Potential profile in the region of QWs and calculated WFs (a) as well as PL spectra of the structure at zero bias (b)-(d).

in the spectrum. There is a broad band containing the contributions of several overlapping peaks which is adjacent to the main peak from its low-energy side. The spectrum fits well by six Gaussians shown in Fig. 1(b) by dashed lines (dash-dotted line represents the resulting contour). The comparison of PL data with the results of calculations of the energy spectrum of the structure allows one to assign peaks at 1.599, 1.588 and 1.576 eV respectively to c2−h1, c1−h2 and c1−h1 excitonic transitions. The high intensities of c2−h1 and c1−h2 transitions correlate with the calculated distributions of WFs presented in Fig. 1(a).

PL peaks at 1.566, 1.552 and 1.543 eV which are at lower energies relative to c1−h1 transition are most probably due to impurities. In the temperature range 20–90 K all but two-particle electron-impurity complexes should be ionized. In particular, the excitonic complexes with neutral impurities which produce the dominant contribution to the impurity PL at low temperatures and high doping levels appears to be thermally dissociated. From these considerations the peak at 1.566 eV next to c1−h1 excitonic transition is most likely due to electron transition from neutral Si atoms to $h1$ subband (Si^0−h1). The peak at 1.552 eV nearest to Si^0−h1 transition is separated from c1−h1 excitonic transition by 24 eV. Since C is main background acceptor in our samples it would appear reasonable to assign peak at 1.552 eV to the c1−C^0 transition. Moreover, because of the comparable shifts of the remaing peak at 1.543 eV from c1−C^0 peak and Si^0−h1 peak relative to c1−h1 transition it is pertinent to ascribe the peak at 1.543 eV to the Si^0−C^0 transition.

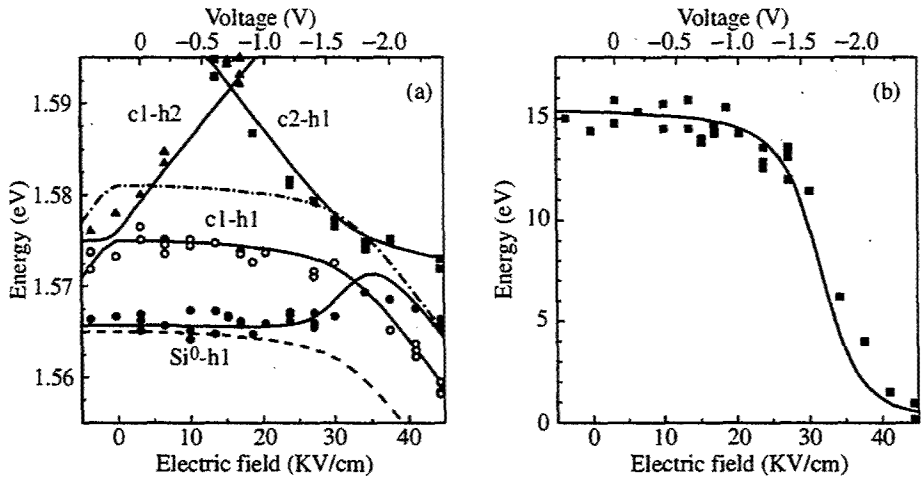

Fig. 2. Theoretical and experimental field dependences of the main transitions in PL spectrum (a) and of E_{imp} (b).

To confirm the impurity nature of low-energy peaks the excitation intensity and temperature dependences of PL were measured. As an example in Fig. 1(c) the PL spectrum of the same sample is shown but measured with the excitation intensity of 12 W/cm^2 and amplification about a fifth as large as it does in spectrum in Fig. 1(b). Indeed, as the excitation intensity increases the contribution of low-energy peaks to the spectrum diminishes as compared to that of c1−h1 transition due to finite amounts of Si donors and C acceptors in QW. Notice that because of weakness of low-energy peaks in spectrum in Fig. 1(c) the good fit in this region is provided by one peak which is designated as Si^0−h1 transition instead of three peaks in Fig. 1(b). The PL spectrum in Fig. 1(d) measured at 90 K and amplification 10 times that of spectrum in Fig. 1(b) illustrates the modification of spectrum with temperature. This spectrum is approximated well-by three Gaussians (dashed lines) which are the contributions of c2−h1, c1−h2 and c1−h1 transitions at 90 K. The absence of impurity states contributions in this spectrum is explained by thermal ionization of donors and acceptors.

3 Ionization energy of Si donor

In the spectrun in Fig. 1(b) taken at $U = 0$ the Si^0−h1 peak and c1−h1 excitonic transition are 10 meV apart. One has to add to this value the exciton binding energy E_{ex} to determine E_{imp}. Our variational calculations taking into account built-in field in the structure provide $E_{ex} \approx 6$ meV, therefore, E_{imp} is close to 16 meV. This is considerably in excess of the values reported by many authors (12–13 meV). The additional increase of E_{imp} in our case is explained by δ-doping which produces the V-shaped potential in the centre of QW. This potential is responsible for the decrease of lower states energies relative to the higher states [ ] and consequently for the increase of E_{imp}. According to our estimates the increase of E_{imp} is as much as 3–4 meV for our samples due to this effect.

In Fig. 2(a) the PL data (points) and the results of calculations (curves) are shown for the field dependences of the main transitions when biases from +0.4 to −2.4 V are applied to the top electrode. The anticrossing of c1−h1 and c2−h1 curves in Fig. 2(a) at the field

strength of 30 kV/cm is of significance for us since in this region the redislocation of electronic WF of lower subband from doped to undoped QW takes place. The calculation in the effective mass approximation yields $E_{imp}(F) = u^2(F)E_0$, where E_0 is impurity ionization energy in single QW with the same parameters as doped QW in our samples. The electric field F dependent coefficient $u(F)$ contains the information regarding the part of electron WF localized in doped QW. This coefficient varies from 1 to 0 and E_{imp} changes accordingly from E_0 to 0. The more sophisticated calculations in the approximation of δ-shaped potential [ ] allows one to refine the previous formula and to calculate the field dependence of Si^0−h1 peak position which is shown in Fig. 2(a) by solid line. The field dependence of impurity peak position without the effect of modification of impurity ionization energy is shown by dashed line for comparison along with the field dependence of c1−h1 edge transition (dash-dotted line). The latter was obtained from the experimental field dependence of c1−h1 exciton peak position having regard to calculated E_{ex}. Referring to Fig. 2(a), in the region of 25–40 kV/cm where the redislocation of electron WF occurs the Si^0−h1 curve approaches rapidly the field dependence of c1−h1 edge transition. This is an evidence of drastic decrease of E_{imp}.

The theoretical and experimental field dependences of E_{imp} obtained as a difference between calculated field dependence of c1−h1 edge transition and the respective theoretical and experimental dependences of Si^0−h1 transitions are shown in Fig. 2(b). One can see from this figure that E_{imp} reaches 15.5 meV in the weak field but rapidly vanishes as field increases. Such dramatic change of E_{imp} is connected with electron WF redislocation with anticrossing of lower subbands in electric field and can't be explained by Stark effect. According to our estimates the latter would produce the E_{imp} variation not exceeding 3 meV.

This work has been supported in part by RFBR, Russian Programme "Physics of Solid State Nanostructures" and State Programme "Integration".

References

[1] V. I. Belyavsky, Yu. V. Kopaev, N. V. Kornyakov and S. V. Shevtsov *JETP Lett.* **61**, 1039 (1995).
[2] R. Sasagawa, H. Sugawara, Y. Ohno, et al. *Appl. Phys. Lett.* **72**, 719 (1998).
[3] Yu. A. Aleshchenko, I. P. Kazakov, V. V. Kapaev, Yu. V. Kopaev, N. V. Kornyakov and A. E. Tyurin *JETP Lett.* **69** 194 (1999).